CHAPTER 25

RADIOGRAPHIC ANALYSIS OF TRANSVERSE PLANE DIGITAL ALIGNMENT FOLLOWING SURGICAL REPAIR OF THE SECOND METATARSOPHALANGEAL JOINT

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MATERIALS AND METHODS

We undertook a retrospective cohort study to evaluate the radiographic results of surgical repair of the unstable second MTPJ. This investigation was not funded by an external sponsor, and was undertaken as part of the lead author's (AYC) residency training requirement.

STUDY POPULATION

The cohort consisted of 49 consecutive patients undergoing second metatarsophalangeal joint (MTPJ) surgical reconstruction on 51 feet. The operations were performed by four attending surgeons (JR, AB, CC, TC) at 4 metropolitan Atlanta surgical facilities (Northlake Medical Center, Northlake Surgery Center, Eastside Medical Center, and the Atlanta Center for Foot and Ankle Reconstruction), between May 21, 1998 and February 3, 2005. Criteria for inclusion in the cohort included the following: males and females who were surgically treated for a chief complaint related to second MTPJ instability. Exclusion criteria included a known acute traumatic etiology for the second ray symptomatology, and Freiberg's infraction due to its theoretical traumatic etiology. All of the patients had been treated conservatively with a combination of treatments that included activity modification, NSAIDs, foot orthoses, taping or ortho-digital splinting, and steroid injections, without satisfactory improvement. All of the patients were deemed appropriate surgical candidates by their managing surgeon, and underwent informed consent for the surgical intervention. Care was taken by the contributing surgeons to safeguard personal identification information related to the individual patients whose data were used in this investigation.

Figure 1. Radiographic transverse plane second metatarsophalangeal joint angle.

PRIMARY AIM AND OUTCOME OF INTEREST

Our primary aim was to identify the second ray surgical intervention that established and maintained the second toe in a parallel relationship with an anatomically normal hallux, as measured by the weightbearing transverse plane radiographic alignment of the second MTPJ. Our outcome of interest, therefore, was the transverse plane second MTPJ angle (transverse plane second MTPJ angle), as measured in degrees on the standard weight-bearing antero-posterior (AP) foot radiograph in the preoperative (Figure 1), immediate postoperative, and long term post-operative periods. We defined the "normal" range for the transverse plane second MTPJ angle to be 0° to $+15^{\circ}$, with a negative angle indicating digital adduction and a positive angle indicating digital abduction. We based this "normal" range of $0\text{-}15^{\circ}$ on the angle that is created between the long axis of the hallux and that of the second toe when a parallel relationship exists between the hallux and second toe, and when a normal hallux abductus angle (HAA) is present.[1-3] In our experience a second ray that displays a transverse plane MTPJ angle that is similar in range to a normal HAA, combined with a rectus second toe that purchases the substrate, results in an acceptable clinical outcome.

The 4 surgeons employed 1 of 8 different combinations of surgical procedures to address second MTPJ instability (Table 1). All of the combinations included, as the fundamental intervention, PIPJ arthrodesis in conjunction with MTPJ release and temporary Kirschner-wire (K-wire) transfixation. The following surgical maneuvers were used in combination with the fundamental intervention to construct 8 different groups of surgical interventions for comparison: FDL tendon transfer, flexor plate repair, flexor plate debridement and placement of a non-absorbable plantar-lateral retention suture, EDB tendon transfer, MTPJ arthroplasty consisting of proximal phalangeal base resection and/or partial metatarsal head resection, Weil osteotomy, and second-to-third syndactyly. If surgical procedures were performed on other structures in addition to those described above for the second ray, they were recorded as ancillary interventions and considered in the analysis.

RADIOGRAPHIC OUTCOMES

The transverse plane second MTPJ angle, measured as the angle created by the intersection of the long axis of the second metatarsal and the long axis of the second proximal phalanx, was quantified on preoperative, immediate postoperative, and long-term postoperative standard anterior-posterior radiographs. All of the radiographic measurements were made by the primary author (AC), using a marking pen and tractograph. We defined a positive radiographic angle as an angle formed between the bisection of the second metatarsal and proximal phalanx with a transverse-plane malalignment in the lateral direction toward the lesser digits. A negative value was given to any malalignment in a medial direction toward the hallux. Preoperative second MTPJ position was also categorized as congruous, subluxated, or dislocated; and additional deformities and their surgical treatments, as noted above, were also identified and considered in the analyses.

RESULTS

Standard AP radiographs of 51 feet in 49 subjects with surgically managed second MTPJ instability were evaluated at a median followup of 24.7 months postoperatively (Table 2). The 2 patients that underwent surgical intervention on both feet had surgery on separate dates for each foot, and did not undergo simultaneous bilateral foot surgery. Table 2, above, displays the surgical and radiographic data used in our analysis. The data indicate that the surgeons resorted to anchoring the flexor plate, and performing a metatarsal osteotomy, more often in the last 2 years than in the first 3 years of the observation period. The overall median preoperative transverse plane second MTPJ angle was -1° (-10°, 8°), whereas the median immediate postoperative angle was 10° (6°, 15°), and the median long-term postoperative angle was 2° (-6°, 11°). We also see that, in the preoperative phase, the median transverse plane second MTPJ angle ranges from -4.5° to 3° for all of the interventions other than MTPJ arthroplasty, which was undertaken on joints that displayed greater malalignment and a median angle of 20°. In the immediate postoperative phase, the MTPJ angle was more tightly clustered and ranged from 2° to 14.5°, with the extensor tendon transfer procedure providing the most balanced alignment (median second MTPJ angle of 2°). Thereafter, in the late postoperative period, the median second MTPJ angle ranged from -3.5° to 14°, with the extensor tendon transfer procedure, once again, affording the most balanced alignment (0.5°).

When we tested the hypothesis that the median of the difference between preoperative and immediate postoperative, and preoperative and late postoperative, and immediate postoperative and late postoperative transverse plane MTPJ angles differed for each foot (matched pairs) (Table 3), using the Wilcoxon signed-rank test, the only statistical differences observed for intervention A were noted when comparing the preoperative angle to the immediate postoperative angle (P = 0.0011) and when comparing the immediate postoperative angle to the late postoperative angle (P = 0.0021); and for intervention C when comparing the immediate postoperative angle to the late postoperative angle (P = 0.0227); and for intervention D when comparing the preoperative angle to the immediate postoperative angle (P = 0.0340) and when comparing the preoperative angle to the late postoperative angle (P = 0.0348); and for intervention G when comparing the preoperative angle to the immediate postoperative angle (P = 0.0173) and when comparing the preoperative angle to the late postoperative angle (P = 0.0491). The data displayed statistically significant improvements in the median preoperative (-1.5°) to early postoperative (9°) transverse plane second MTPJ angle for the fundamental intervention (P = 0.0011).

Similarly, we observed statistically significant improvements in the median preoperative (-5°) to early

Table 1

SECOND RAY SURGICAL INTERVENTIONS.

Intervention	Technical Description of Intervention
A. The fundamental intervention, FI, entailed PIPJ fusion plus MTPJ relocation and K-wire transfixation.	Following transverse tenotomy or Z-lengthening of EDL, the PIPJ is dissected via sectioning of the collateral ligaments and dorsal capsulotomy, after which MTPJ release consisting of either a transverse or "V" capsulotomy combined with transection of the collateral ligaments; followed by resection of the head of the proximal phalanx and base of the middle phalanx with either end-to-end or peg-in-hole arthrodesis with temporary K-wire transfixation of the PIPJ and, if indicated by intra-operative push-up testing, the MTPJ. The K-wire was removed after clinical and radiographic findings indicated the presence of a solid arthrodesis.
B. FI plus flexor digitorum longus tendon transfer or release.	In addition to the fundamental intervention, FDL was either transected via a stab incision plantar to the PIPJ or transferred in one of two fashions. One method involved retrieval of the long flexor after resection of the PIPJ, then splitting FDL longitudinally and transferring the split sections medially and laterally about the proximal phalanx and then reapproximating and anchoring the tendon slips dorsally. The second method entailed harvesting FDL superficial and medial to the MTPJ after which the tendon is sutured to the lateral aspect of the MTPJ.
C. FI plus flexor plate repair.	In addition to the fundamental intervention, the plantar plate was debrided of any grossly attenuated or diseased tissue and the remaining portion reefed using nonabsorbable suture while maintaining the MTPJ in a rectus position, via a plantar incision. Thereafter, the flexor tendon sheath was reapproximated directly over the plantar plate.
D. FI plus flexor plate anchor/retention suture.	In addition to the fundamental intervention, the MTPJ capsule was released medially (including the medial plantar plate) and a lateral portion of the capsule was excised; after which, a nonabsorbable suture was then used in an over-and-over fashion to anchor the lateral portion of the plantar plate to the plantar-lateral aspect of the MTPJ.
E. FI plus extensor digitorum brevis tendon transfer.	In addition to the fundamental intervention, EDB was released at the level of the MTPJ medially and re-attached to the plantar-lateral aspect of the joint where it was secured with a non-absorbable suture.
F. FI plus second MTPJ arthroplasty.	In addition to the fundamental intervention, a 2-3 mm resection of the base of the proximal phalanx was performed and, in cases that displayed gross dorsal osteophytosis and subchondral erosion, a partial (dorsal) metatarsal head resection was performed.
G. FI plus Weil osteotomy.	In addition to the fundamental intervention, a medial transpositional Weil osteotomy was performed on the second metatarsal.
H. FI plus second-to-third syndactyly	In addition to the fundamental intervention, the identical procedure was performed on the third ray, after which the contiguous surfaces of the second and third toes were syndactylized.

Table 2

COHORT DATASET (N = 51)

Pt[1]	Gender[2]	Age (years)	Age category[3]	Dx[4]	Joint type[5]	Preop angle (deg.)	PPR[6]	Surgery date	Surgeon[7]	2nd ray Sx[8]	Adj. Sx[9]	Imm. date[10]	Imm. Angle[11]	Late date[12]	Late angle[13]
1	0	38	0	1	2	6	0	5/21/1998	1	1	2	5/21/1998	6	8/24/1998	-6
2	0	67	3	4	1	-6	0	4/13/1999	1	3	2	4/13/1999	4	5/24/1999	28
3	0	39	0	1	1	22	0	5/20/1999	1	3	2	5/20/1999	-8	6/28/1999	12
4	0	72	4	3	1	-12	0	7/8/1999	1	3	3	7/8/1999	20	10/15/1999	-8
5	0	60	3	3	2	-5	1	7/20/1999	4	2	2	8/25/1999	6	5/11/2001	-6
6	0	63	3	2	0	17	0	9/24/1999	2	7	1	9/24/1999	13	7/19/2000	-8
7	0	65	3	3	2	0	0	11/18/1999	1	1	3	11/18/1999	8	11/27/2000	2
8	0	66	3	3	2	27	0	3/2/2000	1	5	3	3/2/2000	15	3/7/2001	14
9	0	55	2	1	1	-11	0	5/22/2000	4	2	2	6/8/2000	0	4/9/2004	-18
10	0	77	4	1	2	5	0	6/29/2000	3	0	2	6/29/2000	10	5/15/2002	-8
11	0	52	2	3	2	-19	0	9/7/2000	1	3	3	9/7/2000	15	7/6/2004	-2
12	0	48	1	1	1	20	0	12/26/2000	2	5	2	5/19/2000	11	7/29/2003	26
13	0	50	2	3	1	14	0	2/9/2001	2	6	3	2/27/2001	12	12/26/2001	6
14	0	46	1	4	2	-12	0	3/29/2001	1	3	2	3/29/2001	22	5/7/2004	11
15	0	69	3	3	1	-8	0	4/25/2001	4	4	3	4/30/2001	-4	8/19/2004	-6
16	0	43	1	3	1	-1	0	5/1/2001	4	4	3	6/11/2001	8	10/15/2001	7
17	1	40	1	2	0	10	0	12/20/2001	4	6	1	1/30/2002	21	7/8/2002	34
18	0	36	0	1	0	14	0	7/9/2002	2	6	2	7/24/2002	26	9/5/2002	18
19	0	50	2	3	2	19	0	8/2/2002	1	5	3	8/2/2002	13	1/24/2003	20
20	0	71	4	3	2	-26	0	9/6/2002	2	7	2	9/16/2002	16	7/7/2003	4
21	0	59	2	3	1	-1	1	11/5/2002	4	2	2	12/17/2002	6	10/20/2003	4
22	0	56	2	3	2	-24	1	1/7/2003	4	6	2	1/17/2003	10	7/11/2003	-4
23	0	70	4	1	1	0	0	1/14/2003	4	0	2	2/26/2003	8	10/8/2003	-4
24	0	44	1	0	1	-1	0	4/18/2003	2	6	0	5/8/2003	12	6/19/2003	8
25	0	55	2	3	1	3	0	5/27/2003	3	0	2	6/3/2003	5	5/21/2004	-5
26	0	68	3	3	1	-6	0	8/4/2003	1	3	1	8/4/2003	0	2/3/2004	-6
27	1	56	2	0	1	-10	0	10/27/2003	1	6	0	10/27/2003	12	6/11/2004	-2
28	0	46	1	0	2	-1	0	12/2/2003	3	0	0	12/2/2003	17	5/10/2004	0
29	0	73	4	1	2	-14	0	12/18/2003	3	0	2	12/18/2003	4	3/18/2004	-6
30	1	50	2	4	1	-4	1	12/23/2003	4	2	0	2/9/2004	10	12/30/2004	3
31	0	55	2	3	2	-15	0	12/30/2003	4	6	3	2/5/2004	30	12/30/2004	19
32	0	55	2	1	1	-4	0	2/2/2004	1	3	2	2/2/2004	10	2/22/2005	16
33	0	62	3	3	2	-35	0	2/3/2004	3	0	3	2/10/2004	-3	3/2/2005	-7
34	1	57	2	1	0	1	0	2/9/2004	1	3	2	2/9/2004	15	11/26/2004	0
35	0	47	1	3	1	10	0	2/10/2004	3	0	2	2/19/2004	11	12/8/2004	6
36	0	63	3	3	2	8	1	2/17/2004	4	2	2	3/30/2004	16	2/24/2005	-1
12	0	70	4	1	1	-10	0	2/19/2004	3	0	2	3/5/2004	11	7/14/2004	-6
37	0	60	3	1	1	-2	0	3/2/2004	3	0	2	3/9/2004	8	6/16/2004	0
38	0	75	4	1	2	-10	0	5/7/2004	3	0	2	5/7/2004	10	2/2/2005	-11
39	0	66	3	1	1	-1	0	8/12/2004	1	3	2	8/12/2004	16	10/29/2004	6
40	0	70	4	3	2	-18	0	8/23/2004	1	5	3	8/23/2004	4	11/4/2004	-4
41	1	64	3	0	1	11	0	9/16/2004	1	3	0	9/16/2004	0	11/30/2004	11
42	1	50	2	1	1	16	1	10/19/2004	4	2	1	12/1/2004	-18	1/19/2005	-19
43	0	50	2	1	1	-3	0	11/23/2004	2	6	2	11/23/2004	13	1/31/2005	-3
44	0	49	1	3	2	35	0	12/21/2004	2	5	3	12/21/2004	2	2/21/2005	7
45	0	56	2	1	1	-3	0	12/30/2004	1	3	2	12/30/2004	22	2/23/2005	13
46	0	73	4	1	1	-12	0	1/3/2005	1	3	2	1/3/2005	15	3/25/2005	0
47	0	65	3	1	1	-2	0	1/20/2005	3	0	2	1/20/2005	10	2/21/2005	3
48	0	58	2	2	2	0	0	1/27/2005	3	0	1	1/27/2005	12	3/7/2005	6
49	0	54	2	1	1	-5	0	1/27/2005	3	0	2	2/4/2005	7	3/9/2005	4
40	0	55	2	1	1	6	0	2/3/2005	3	0	2	2/3/2005	6	3/17/2005	11

Table 2 continued

[1]Unique patient identifier, designated 1-49.
[2] Sex (0 = female, 1 = male).
[3] Age category (0 = [< 40 years], 1 = [40-49 years], 2 = [50-59 years] , 3 = [60-69], 4 = [≥70 years]).
[4] Diagnosis (0 = hammertoe (HT) second only, 1 = HT second + 1st ray (hallux valgus, hallux limitus, hallux varus, nonunion 1st MTPJ, painful internal fixation device, failed implant in 1st ray); 2 = HT second + lesser ray (other hammertoes, neuroma, tailor's bunionette); 3 = HT second + 1st ray (hallux valgus, hallux limitus, hallux varus, nonunion 1st MTPJ fusion, painful internal fixation device, failed implant) + lesser ray (other hammertoes, neuroma, tailor's bunionette); 4 = all other pedal diagnoses).
[5] Joint type (0 = congruous, 1 = subluxated, 2 = luxated).
[6] Plantar plate rupture (0 = not present, 1 = present).
[7] Surgeon (designated 1-4, for each of the four contributing surgeons).
[8] Second ray surgery (0 = PIPJ fusion + MTPJ relocation and K-wire transfixation [the fundamental intervention, designated FI]; 1 = FI + flexor tendon transfer or tenotomy; 2 = FI + flexor plate repair; 3 = FI + flexor plate anchor suture; 4 = FI + extensor tendon transfer into metatarsal; 5 = FI + MTPJ arthroplasty; 6 = FI + Weil metatarsal osteotomy; 7 = FI + syndactyly).
[9] Adjunct surgical procedures performed on areas other than the second ray (0 = lesser ray; 1 = first ray; 2 = lesser and first rays; 3 = all other areas of the foot).
[10] Immediate postoperative radiographic date (mo.dy.yr).
[11] Immediate postoperative transverse plane MTPJ angle (degrees).
[12] Late postoperative radiographic date (mo.dy.yr).
[13] Late postoperative transverse plane MTPJ angle (degrees)

postoperative (15°) transverse plane second MTPJ angle for the fundamental intervention plus placement of a plantar lateral retention suture to secure the realigned flexor plate (P = 0.0340). Moreover, the retention suture maintained a statistical improvement from the preoperative (-5°) phase to the late followup (8.5°) observation (P = 0.0348). Still further, statistical differences were achieved (-2° to 12.5°, P = 0.0173) and maintained (-2° to 7°, P = 0.0491) with the use of the Weil metatarsal osteotomy in conjunction with the fundamental intervention. On the other hand, we noted statistically significant reductions in correction of the median transverse plane second MTPJ angle going from the early (9°) to the late (-2°) postoperative periods for fundamental intervention (P = 0.0021), as well as from early (6°) to late (-3.5°) postoperative periods for the fundamental intervention plus repair of the flexor plate (P = 0.0227).

The overall median degree of correction for all of the procedures in the immediate postoperative period was 12° (8°, 22°), whereas the overall median correction over the course of the followup period was 8° (4°, 14°), and this difference was statistically significant (P = 0.0004). In essence, over time, the overall median correction diminished between the immediate postoperative and the late postoperative periods. Clinically, the flexor plate anchor suture and second to third syndactyly achieved the greatest degrees of early postoperative correction, 21° and 23°, respectively. However, only the syndactyly maintained this high degree of transverse plane correction (27.5°) over the course of the observation period. There were no statistically significant differences between the degrees of correction achieved with the various interventions with respect to the early (P = 0.227), and late (P = 0.247), postoperative periods.

PIPJ arthrodesis combined with second MTPJ relocation and K-wire transfixation served as the fundamental intervention (FI). The FI was performed on all 51 feet, 14 (27.45%) of which underwent this basic intervention alone. The remaining 37 feet underwent the FI in combination with the following additional surgical maneuvers: flexor tendon transfer or flexor set release, n = 2 (3.92%); flexor plate repair, n = 6 (11.76%); plantar-lateral retention suture, n = 12 (23.53%); extensor tendon transfer, n = 2 (3.92%); MTPJ arthroplasty, n = 5 (9.8%); metatarsal osteotomy, n = 8 (15.69%); second-to-third syndactyly, n = 2 (3.92%). Overall, the median angular correction for all second MTPJ interventions was 2° (-6°, 11°). The intervention involving use of the FI in conjunction with MTPJ arthroplasty yielded the most long-term angular correction, as determined by abductus realignment of the second MTPJ, and this combination of maneuvers effected a median long-term transverse plane MTPJ angle 14° (-7°, 20°). This intervention was followed, in descending order of the amount of angular correction, by use of the FI in combination with: placement of a plantar-lateral anchor suture, 8.5° (-1°, 12.5°); metatarsal osteotomy, 7 (-2.5°, 18.5°); extensor tendon transfer, 0.5° (-6°, 7°); flexor tendon transfer, -2° (-6°, 2°), syndactyly, -2 (-8°, 4°); and repair of the flexor plate, -3.5o (-18°, 3°). Alone, the FI effected a median long-term transverse plane MTPJ angle of -2° (-6°, 4°).

We did not observe a statistically significant difference in the preoperative period when the transverse plane second MTPJ angle was compared between the eight second ray surgical intervention groups (P = 0.279). There was, however, a statistically significant difference in the immediate postoperative period when the transverse plane second MTPJ angle was compared between the eight

Table 3

COMPARISON OF THE RADIOGRAPHIC TRANSVERSE PLANE SECOND MTPJ ANGLE (MEDIAN AND INTERQUARTILE RANGE) BY OBSERVATION PERIOD AND SECOND RAY INTERVENTION* (N = 51)

Overall ** (N = 51, 100%)		**P-value** **
Preop angle = -1° (-10°, 8°)	Early postop angle = 10° (6°, 15°)	<0.0001
Preop angle = -1° (-10°, 8°)	Late postop angle = 2° (-6°, 11°)	0.0365
Early postop angle = 10° (6°, 15°)	Late postop angle = 2° (-6°, 11°)	0.0001
Intervention A (n = 14, 27.5%)		
Preop angle = -1.5° (-10°, 3°)	Early postop angle = 9° (6°, 11°)	0.0011
Preop angle = -1.5° (-10°, 3°)	Late postop angle = -2° (-6°, 4°)	0.2711
Early postop angle = 9° (6°, 11°)	Late postop angle = -2° (-6°, 4°)	0.0021
Intervention B (n = 2, 3.9%)		
Preop angle = 3° (0°, 6°)	Early postop angle = 7° (6°, 8°)	0.3173
Preop angle = 3° (0°, 6°)	Late postop angle = -2° (-6°, 2°)	0.6547
Early postop angle = 7° (6°, 8°)	Late postop angle = -2° (-6°, 2°)	0.1797
Intervention C (n = 6, 11.8%)		
Preop angle = -2.5° (-5°, 8°)	Early postop angle = 6° (0°, 10°)	0.3441
Preop angle = -2.5° (-5°, 8°)	Late postop angle = -3.5° (-18°, 3°)	0.2932
Early postop angle = 6° (0°, 10°)	Late postop angle = -3.5° (-18°, 3°)	0.0227
Intervention D (n = 12, 23.5%)		
Preop angle = -5° (-12°, 0°)	Early postop angle = 15° (2°, 18°)	0.0340
Preop angle = -5° (-12°, 0°)	Late postop angle = 8.5° (-1°, 12.5°)	0.0348
Early postop angle = 15° (2°, 18°)	Late postop angle = 8.5° (-1°, 12.5°)	0.3876
Intervention E (n = 2, 3.9%)		
Preop angle = -4.5° (-8°, -1°)	Early postop angle = 2° (-4°, 8°)	0.1797
Preop angle = -4.5° (-8°, -1°)	Late postop angle = 0.5° (-6°, 7°)	0.1797
Early postop angle = 2° (-4°, 8°)	Late postop angle = 0.5° (-6°, 7°)	0.1797
Intervention F (n = 5, 9.8%)		
Preop angle = 20° (19°, 27°)	Early postop angle = 11° (4°, 13°)	0.3452
Preop angle = 20° (19°, 27°)	Late postop angle = 14° (7°, 20°)	0.8927
Early postop angle = 11° (4°, 13°)	Late postop angle = 14° (7°, 20°)	0.5002
Intervention G (n = 8, 15.7%)		
Preop angle = -2° (-12.5°, 12°)	Early postop angle = 12.5° (12°, 23.5°)	0.0173
Preop angle = -2° (-12.5°, 12°)	Late postop angle = 7° (-2.5°, 18.5°)	0.0491
Early postop angle = 12.5° (12°, 23.5°)	Late postop angle = 7° (-2.5°, 18.5°)	0.0684
Intervention H (n = 2, 3.9%)		
Preop angle = -4.5° (-26°, 17°)	Early postop angle = 14.5° (13°, 16°)	0.6547
Preop angle = -4.5° (-26°, 17°)	Late postop angle = -2° (-8°, 4°)	0.6547
Early postop angle = 14.5° (13°, 16°)	Late postop angle = -2° (-8°, 4°)	0.1797

* A = fundamental intervention (FI) = (PIPJ fusion and MTPJ release with K-wire transfixation); B = FI + flexor tendon transfer or set release; C = FI + flexor plate repair; D = FI + flexor plate anchor suture; E = FI + extensor tendon transfer; F = FI + MTPJ arthroplasty; G = FI + metatarsal Weil osteotomy; H = FI + second-to-third syndactyly.

** Overall represents all interventions combined; interventions, A-H, are defined in detail in Table 1, above.

*** Wilcoxon signed rank test.

surgical intervention groups ($P = 0.016$). Thereafter, in the late postoperative period, a statistically significant difference was, once again, not observed between the 8 surgical intervention groups ($P = 0.515$).

Consideration of the prevalence of the outcome as it relates to a given risk factor showed higher proportions of patients achieving the outcome when they were ages 40-49 years (75%), or when the cohort was dichotomized by age less than the median 56 years (47.83%) as compared with age ≥ 56 years (42.86%). Moreover, the proportion of patients not achieving the outcome was considerably less in the presence of concomitant first ray pathology (33%), or when adjunct first ray surgery was undertaken (20%), as compared with isolated second ray pathology (75%) or when only second ray surgery was undertaken (80%). The presence of a ruptured plantar plate also decreased the prevalence of the outcome (33.33%). Furthermore, the prevalence of the outcome generally increased over the course of the study, ranging from 20-38% for the years 1998-2000, to 30-60% for the years 2001-2005. Still further, deformities requiring repair of the flexor plate or metatarsal osteotomy displayed lower proportions of patients achieving the outcome, 33.33% and 25%, respectively. Patients displaying a preoperative transverse plane second MTPJ angle adducted greater than 15° fared worse than those displaying an angle abducted greater than 15°, 20% and 50% respectively; while those displaying an angle between -15° (adducted) and +15° (abducted), achieved the outcome 45% of the time. Lastly, every patient displaying an immediate postoperative transverse plane second MTPJ angle measuring > 15° adducted failed to achieve the outcome.

Hypothesis testing did not reveal any statistically significant differences between the risk factor groups relative to each group achieving the outcome. Because of the lack of true independence between our risk factor variables and the patients comprising the cohort (two of the patients underwent bilateral foot surgery), rather than merely using single-variable (unadjusted) and multiple-variable (adjusted) logistic regression to assess the magnitude of the effect of a given risk factor on the outcome, both fixed effects and random effects models using generalized estimation equations (GEE) were used to more conservatively calculate the effect estimates.[4] Univariate GEE did not reveal any statistically significant risk factors for failure to achieve the outcome of a transverse plane second MTPJ angle of 0°-15° in the late postoperative period. Adjusting the analysis for multiple selected variables, however, did reveal several statistically significant risk factors. We observed greater odds of achieving the outcome if the patient was less than 40 years of age, odds ratio (OR) 4439.5 (95% confidence interval [95% CI] 1.76, >10,000). On the other hand, we observed lesser odds of achieving the outcome if the patient underwent second metatarsal osteotomy, OR 0.01 (95% CI 0.0002, 0.71); and when the patient underwent concomitant correction of first ray deformity, OR 0.0013 (95% CI <0.0001, 0.55).

Several interaction terms were also analyzed using the GEE, including: age and sex, age and preoperative transverse plane second MTPJ angle, age and second ray procedural selection, age and adjunct surgery, preoperative transverse plane second MTPJ angle and second ray procedural selection, and, lastly, preoperative transverse plane second MTPJ angle and adjunct surgery. None of these interaction terms was statistically significant ($P \geq 0.05$). With the exception of the interaction between age and sex, moreover, none of the effect estimates varied by more that 10-15%, indicating the presence of confounding between the effect of age and sex on the outcome.[5]

SENSITIVITY ANALYSIS

As with all retrospective cohort studies, our results are subject to the effects that hypothetical unmeasured variables could have on the data. Therefore, we undertook a sensitivity analysis using the method of Greenland.[6-8] We hypothesized the presence of an unmeasured variable and input its prevalence, ranging from 0.1-0.4 in both the exposed (to the measured risk factor) and unexposed (to the measured risk factor) groups; and its outcome OR (ratio of the odds of the outcome in the presence of the unmeasured risk factor to the odds of the outcome in the absence of the unmeasured risk factor), ranging from 5-7, into a sensitivity analysis calculator that we programmed in a readily available spreadsheet application (Microsoft Excel) (The Greenland sensitivity analysis calculator is available upon request). We then analyzed the influence that such a hypothetical unmeasured variable would have on the odds ratio for observing a late radiographic transverse plane second MTPJ angle of 0°-15° (the outcome of interest), in the presence of a ruptured plantar plate or a preoperative transverse plane second MTPJ angle of 0°-15° (2 of our measured covariates). With respect to the presence of a ruptured plantar plate, the odds ratio for the outcome changed by more that 10-15% in the presence of the unmeasured variable when the prevalence of the unmeasured variable was >25% in either the exposed and/or unexposed groups. Similarly, with respect to the presence of a preoperative transverse plane second MTPJ angle outside of the 0°-15° range, in either the positive (abduction) or negative (adduction) direction, the OR for the outcome changed by more that 10-15% when the prevalence of the hypothetical unmeasured variable was >25% in either the exposed and/or unexposed groups. The results of this sensitivity analysis indicate that our results are resistant to the influence that an unmeasured variable would impart upon our retrospective data, up to a prevalence of the unmeasured variable of approximately 25% in either the exposed or unexposed measured covariate groups.

DISCUSSION

Second MTPJ instability is a common and challenging pathology encountered by the reconstructive foot surgeon. Our clinical experience has led us to be concerned with the long term transverse plane alignment of the second ray, and this is particularly of concern in cases involving advanced second MTPJ instability, as is encountered in the cross-over second toe deformity. Despite our appreciation of the importance of the sagittal and frontal plane alignment, as well as the range of motion and purchase power of the second toe, the goal of this particular investigation was to analyze current procedures used in the repair of second MTPJ instability as measured by the radiographic transverse plane second MTPJ angle. To this end, we considered a normal radiographic second transverse plane second MTPJ angle as 0°-15°, and based this range on a parallel and rectus alignment of the hallux and second toe. Furthermore, we defined any long-term post-surgical result identified within this range as the desired radiographic result of realignment of the second MTPJ, and used this as the outcome in our investigation.

Over the course of the study, no statistically significant trend was observed with respect to one particular second ray surgical intervention being used more, or less, than any other. Interestingly, the extensor tendon transfer procedure was used in only 2 patients during a single year (2001) over the course of the study. Furthermore, inspection of the results of the comparisons displayed statistical differences where achieved when we compared the overall transverse plane second MTPJ angle between the preoperative and immediate postoperative, preoperative and late postoperative, and immediate post-operative and late postoperative observation periods.

Moreover, the overall direction of change was from a negative (adducted) preoperative alignment to a positive (abducted) postoperative alignment; and it appears as though the angle was over corrected in the direction of abduction at the time of surgery. As the postoperative period progressed, however, the degree of immediate postoperative abduction decreased to a less abducted alignment by the time of the late postoperative radiograph. Inspection of these same comparisons for each of the specific categories of second ray surgical intervention indicates that, for the preoperative to immediate postoperative phase, statistically significant differences were observed for PIPJ fusion and MTPJ release with K-wire transfixation (the fundamental intervention, FI), as well as for the FI combined with flexor plate anchor suture or with a Weil metatarsal osteotomy. During this period the direction of angular correction was generally negative (adducted) to positive (abducted), except for MTPJ arthroplasty which was highly abducted in the preoperative phase and reduced to a less abducted alignment via the intervention.

In our cohort, for severe MTPJ abductus in the preoperative period, MTPJ arthroplasty was used for approximately 10% of the cases. In regard to the immediate postoperative to late postoperative phase, statistical differences were achieved with the FI, use of the flexor plate anchor suture, and the Weil osteotomy. As for the preoperative to late postoperative period, all of the interventions except the use of an anchor suture and the Weil osteotomy resulted in the maintenance of statistically significant differences in the MTPJ angle. It appears as though the best maintenance of a balanced alignment, ideally defined as a late followup transverse plane second MTPJ angle = 0°, was achieved using; or this foundation intervention combined with flexor tendon transfer or flexor set release, flexor plate anchor suture, extensor tendon transfer, or second-to-third syndactyly. These 4 interventions resulted in a range of median second MTPH angles ranging from -2° to 8.5°.

In regard to absolute magnitude of correction, the overall median degree of correction for all of the procedures in the immediate postoperative period was 12° (8°, 22°), whereas the overall median correction over the course of the followup period was 8° (4°, 14°), and this difference was statistically significant (P = 0.0004). In essence, over time, the overall median correction diminished between the immediate postoperative and the late postoperative periods. Clinically, the flexor plate anchor suture and second to third syndactyly achieved the greatest degrees of early postoperative correction, 21° and 23°, respectively. However, only the syndactyly maintained this high degree of transverse plane correction (27.5°) over the course of the observation period. There were no statistically significant differences between the degrees of correction achieved with the various interventions with respect to the early ($P = 0.227$), and late ($P = 0.247$), postoperative periods.

No statistically significant differences were noted when we compared the transverse plane second MTPJ angle between the intervention groups in the preoperative phase ($P = 0.279$), indicating that the surgeons did not necessarily choose the intervention that was undertaken based on overt differences in this angle. There was, however, a statistically significant ($P = 0.016$) difference identified when we compared the immediate postoperative transverse plane second MTPJ angle between the intervention groups, indicating that these early differences were most likely due to the choice of the intervention employed. Once again, in the late postoperative phase, no statistical differences were observed when we compared the second MTPJ angle between the intervention groups ($P = 0.515$). These findings suggest that the various surgical procedures differed in their ability to balance the second MTPJ, or that the choice of procedure varied by the degree of second MTPJ malalignment. In all likelihood, it is a combination of both of these factors that influences the outcome. Furthermore, these findings imply that the choice of surgical intervention did not significantly influence the outcome as the duration of time from the day of surgery increased (apparent loss of correction over the followup period).

Achieving the outcome was promoted by a patient age less than 50 years, by undergoing operative intervention in the years 2001-2005, and by the presence of a preoperative transverse plane second MTPJ angle ranging from negative (adducted) 15° to positive (abducted) 15°. In other words, younger patients did better than did older patients, surgeons appear to have improved over time with respect to realigning the second MTPJ, and a transverse plane MTPJ angle within 15° of neutral was more readily corrected and maintained. Achieving the outcome was inhibited by the presence of concomitant first ray pathology or when adjunct first ray surgery was undertaken, the presence of a ruptured plantar plate, deformities requiring metatarsal osteotomy, a preoperative transverse plane second MTPJ angle adducted greater than 15°, and an immediate postoperative transverse plane second MTPJ angle adducted > 15°. The prevalence data also revealed that the majority (92.2%) of second MTPJs were either subluxated or luxated in the preoperative state. These results imply that the crossover second toe deformity combined with hallux abductovalgus HAV is associated with a reduced likelihood of achieving a balanced second MTPJ in both the early and late postoperative periods.

Although hypothesis testing did not reveal any statistically significant differences between the risk factor groups relative to achieving the outcome, several clinically significant differences (≥10% qualitative difference between the groups) were noted. Risk factors that clinically decreased the likelihood of achieving the outcome included female sex, age greater than 50 years, and again age greater than 70 years, the presence of first ray pathology, second MTPJ subluxation or luxation, plantar plate rupture, surgery in the years 2001-2002, and deformity warranting use of the flexor plate anchor suture or the Weil osteotomy.

We used generalized estimation equations, rather than logistic regression, to analyze the effect of any given risk factor, as well as multiple risk factors, on the likelihood of achieving the outcome. We chose to use GEE in order to account for the lack of true independence between our data, in light of the fact that two of our patients underwent bilateral foot surgery at separate settings during the study period. The univariate GEE regression models did not reveal any statistically significant risk factors relative to achieving a transverse plane second MTPJ angle of 0°-15° in the late postoperative period. Therefore, we used multiple risk factors that we had selected a priori, based on our clinical judgment and what we felt were biologically important patient and deformity characteristics, in our multiple variable GEE regression model. These included patient age category, preoperative transverse plane second MTPJ angle, second ray surgical intervention/s, adjunct surgical intervention/s, and the duration of followup. The adjusted (multiple variable) analysis revealed statistically significantly greater odds of achieving the outcome if the patient was less that 40 years of age (OR 4439.5; 95% CI 1.76, >10,000), and statistically significantly reduced odds of achieving the outcome if the patient required second metatarsal osteotomy (OR 0.01; 95% CI 0.0002, 0.71) or concomitant correction of a first ray deformity (OR 0.0013; 95% CI <0.0001, 0.55). The wide confidence intervals about these point estimates indicate a lack of precision and suggest that, despite noting certain statistical differences, our sample size was rather small.

In addition to a relatively small sample size, this retrospective cohort study has other limitations, as well. We focused our quantitative analysis on transverse plane alignment and did not thoroughly consider the influence of sagittal plane realignment on the structure and function of the second MTPJ. Some of our patients underwent rather short followup periods (median 174 days, range 31-1,381 days), although our main emphasis was on the effectiveness of the surgery balancing the transverse plane alignment of the second MTPJ.

Moreover, we did not measure actual range of motion, plantar pressures, purchase strength of the second ray, duration of pin stabilization, or wound complications. Furthermore, we did not employ the use a health measurement instrument that has previously been shown to produce valid information, such as the Bristol Foot Score, the Medical Outcomes Study Short Form 36, or the McGill Pain Questionnaire.

Finally, as with all retrospective cohort studies, it is important to consider the potential influence that unmeasured variables may have had on the results of the study. For this reason, we undertook a sensitivity analysis that indicated our results to be rather resistant to the potential influence of a hypothetical unmeasured variable. Specifically, our results would only become vulnerable to change in the presence of an unmeasured variable that had a very strong association with the outcome (OR 5-7), and only if the unmeasured variable were to be present in greater than 25% of either the exposed or unexposed measured covariate groups. Understanding these limitations, we still feel that these results, much like pilot data, can be useful to future investigators. To date, we are not aware of any other investigation that compares the relationship of a variety of surgical interventions to the radiographic transverse plane alignment of the second ray in the preoperative, immediate postoperative, and long term postoperative periods. We contend that the results of this investigation can be used by subsequent investigators to design randomized controlled trials related to the treatment of, and larger cohort and cross sectional investigations related to the diagnosis of, second MTPJ instability and malalignment.

In conclusion, second MTPJ instability remains a difficult pathology to surgically manage, and a wide range of interventional approaches are available for the treatment of this condition. One of the goals of surgical repair of the unstable and imbalanced second MTPJ is restoration of the transverse plane alignment of the joint. We have shown that patients presenting with this deformity have a clinically and statistically increased likelihood of achieving a balanced MTPJ if they are less than 50 years of age, do not have concomitant first ray pathology that warrants surgical correction, and do not have second ray pathology that requires repair of the flexor plate or metatarsal osteotomy. Combined with PIPJ arthrodesis, MTPJ soft tissue release, and K-wire transfixation, the following second MTPJ surgical interventions created the greatest amount of transverse plane realignment: MTPJ arthroplasty, 14°; placement of a plantar lateral anchor suture, 8.5°; and Weil metatarsal osteotomy, 7°. The ability of these procedures to maintain this high degree of correction was, however, questionable; whereas second-to-third syndactyly displayed the best maintenance of correction over time. The results of this study should be useful to surgeons treating this condition, and can be used in the design of future investigations into the etiology, diagnosis, and treatment of second MTPJ instability and malalignment.

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